LARGE SCALE STRUCTURE AND X-RAY CLUSTERS OF GALAXIES

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Abstract. I review [1] recent progress in the study of the large-scale structure of the Universe through the distribution of clusters of galaxies, concentrating on new results using X-ray selected samples. After discussing the importance of understanding the properties of the tracers used to map structure and their relation to the underlying mass, I elaborate on the advantages and disadvantages of clusters of galaxies to this end. I then present the most recent estimates of the power spectrum and correlation function of X-ray clusters in the local ($z \lesssim 0.2$) Universe, and their implications for cosmological models. Finally, I briefly summarize most recent results from deep X-ray surveys as probes of the evolution of structure and highlight current ongoing observational efforts in this field.

1 Introduction

Our quest for understanding the origin and evolution of galaxies and larger–scale structures is based on the exploration of large volumes of space through redshift surveys of luminous objects. This short review concentrates on using clusters of galaxies as the basic bricks by which to study large-scale structure (LSS hereafter) on the largest accessible scales. In fact, with mean separations $\sim 10\ h^{-1}$ Mpc, clusters of galaxies are ideal objects for sampling efficiently long–wavelength ($\lambda \sim 50 - 100\ h^{-1}$ Mpc) density fluctuations over large volumes, i.e. well in the linear regime where inhomogeneities are expected to fully reflect initial conditions as they emerged at recombination. This means that, for example, we do not necessarily need to go through n–body simulations to produce reliable model predictions for the clustering of clusters, but can use analytic approximations with sufficient accuracy [45, 48]. The second important advantage, which will be discussed at some length later in the text, is that clusters can be selected directly through their X-ray luminosity, a quantity that correlates well with their mass [7]. This is not what happens with galaxies, where luminosity is usually a measure of star formation efficiency, rather than of total mass itself. At the same time, with respect to the loose optical definition of a cluster, X-ray selection provides the ability to select samples with a well–defined selection function, essentially that of a flux–limited sample as in the case of galaxy surveys. On the other hand, clusters provide a *biased* view of clustering: they only represent the very high peaks of the global density field, such that their variance is amplified with respect to galaxies (and of course, mass) as first described by Nick Kaiser [36]. Therefore, they miss the small–scale details of the LSS (that can be complementarily better studied through galaxy surveys). Nevertheless, for the same reason the cluster distribution might provide an enhanced view of possible low–amplitude features in the clustering spectrum on very large scales.

This review inevitably reflects a personal perspective and covers a limited amount of work. However, an effort was made to provide references to complementary topics, as e.g. galaxy surveys and optically selected clusters. Using these, the interested reader can surely enlarge the restricted view of large-scale structure presented here. I also apologize to those colleagues whose work is not adequately represented in this paper.

2 Tracing Light vs. Tracing Mass

Even when studying the distribution of galaxies through redshift surveys (see the review by Da Costa in this same volume), one should always be aware that what is being described is the clustering of

[1] To appear in *Where's the Matter? Tracing Dark and Bright Matter with the New Generation of Large Scale Surveys*, proc. of meeting held in Marseille (June 2001), M. Treyer & L. Tresse eds., Frontier Group

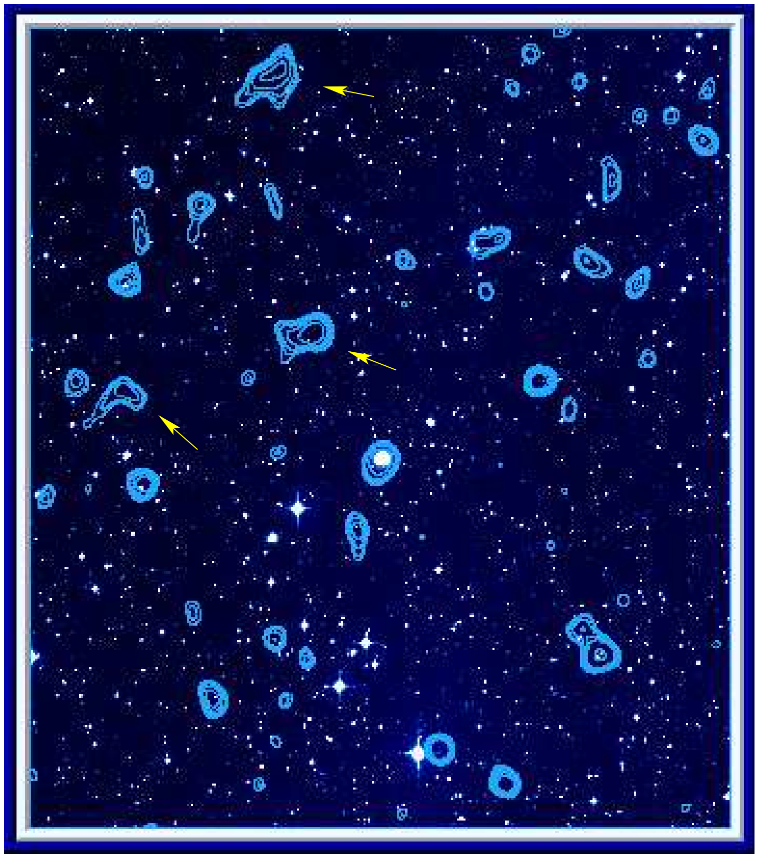

Figure 1: The visible and X-ray appearance of a 30'× 30' patch of sky, as seen respectively on the DSS2 sky atlas (background image) and by the ROSAT satellite HRI instrument (contours, flux limit $\sim 10^{-14}$erg s^{-1} cm^{-2}). About 90% of the X-ray sources in this picture correspond to objects at cosmological distances: in turn, more than 90% of these are active galactic nuclei (typically QSO's at $z > 1$), while a few are distant clusters of galaxies. The latter can be distinguished on the basis of their X-ray extension and in this specific case a wavelet detection algorithm finds three significant cluster candidates, marked by the arrows [40].

a specific class of objects, not of the matter. We know for example that infrared–selected galaxies show a weaker clustering with respect to optically–selected galaxies [32], or that elliptical galaxies are more clustered than spirals [24, 27], or that high-redshift Ly-break selected galaxies look (at $z = 3$) as clustered as nowadays normal galaxies [21, 26]. In other words, with redshift surveys of visible objects we always study the distribution of *tracers* of the LSS. The relation to the mass distribution depends on the kind of tracer we are using, such that the clustering in the light will be in some way proportional to the clustering in the mass. The proportionality between these two distributions is expressed through the *bias* function, in general a function of scale and cosmic epoch. One of the simplest possibilities, which is shown to work reasonably well in the local Universe, is that of a statistical *bias parameter* b independent of scale relating the variances in galaxy counts and in the mass:

$$\left(\frac{\delta n(R)}{\langle n\rangle}\right)_{rms} = b\left(\frac{\delta\rho(R)}{\langle\rho\rangle}\right)_{rms} \tag{1}$$

A fair amount of work has been dedicated to the problem of galaxy biasing during the last fifteen years, both theoretically (e.g. [73]) and observationally (e.g. establishing that for "normal" optically selected galaxies we have $b \simeq 1 - 1.5$ over a fair range of scales [3]). However, understanding the physical origin of the bias is not an easy task, as it involves comprehending the details of how the mass of a galaxy translates into the visible stellar light we use to select it for our surveys. Despite the great advances of the last few years in our knowledge of the early phases of galaxy formation [19], we are still very ignorant about the details of star formation and evolution within galaxies, and as a consequence b remains a free parameter when comparing galaxy clustering to the models.

3 Clusters of Galaxies as Tracers of LSS

Clusters of galaxies have a honourable history as an alternative, complementary tracer of LSS. Although one could spend endless discussions on the semantic of the word "structure" and argue that only galaxies do describe it properly, it is in fact a mere question of "spatial resolution" and of the scales on which we want to focus our attention. Galaxies are best for the fine details, but (even in the 2dF and SDSS era[2]) it is difficult to fully cover large volumes of space using galaxy redshift surveys, because measuring galaxy redshifts costs time. Groups and clusters are much more efficient to cover large volumes, as they are sparser objects, and are therefore excellent for studying the gross structure and its statistical properties in the weak clustering regime. Since clustering extends to scales of the order of 1 Gpc, there is a good deal of structure to be "seen" and measured using such sparse tracers (note e.g. the chains of clusters visible both in the data and simulations of Figs.2 and 6). Also, we are used to the rarity of very rich, massive clusters, but in fact this is just a limitation of current X-ray surveys. An all–sky X-ray survey to a sufficiently faint flux limit ($\sim 10^{-14}$ erg s^{-1} cm^{-2}, i.e. two orders of magnitude fainter than the current ROSAT All–Sky Survey) would provide a finer description of structures connecting rich clusters out to $z \sim 0.3$, detecting chains of faint X-ray groups as pearls on a necklace.

But, are clusters and groups so well defined as a class to be used to trace LSS in a homogeneous and statistically reliable way? If defined in the optical as galaxy overdensities, clusters are in fact just a "collection of pieces", thus intrinsically prone to subjective interpretations and biases [1, 74, 64]. Overcoming at least the human intervention in this process prompted the construction of automatic cluster catalogues, based on the first digitised galaxy photographic surveys produced in the UK, notably the EDCC [42] and APM [13] catalogues (see also contributions by Gal [20] and Kim [37] in this volume). However, it is when we come to estimating its mass that we are faced with the intrinsic ambiguity of the optical definition of a cluster. Richness (i.e. the number of galaxies observed in projection within a fiducial radius, corrected for the expected background contamination) has a poor correlation with mass [7]. A much better way would be to measure the velocity dispersion of the cluster galaxies, which at equilibrium (no galaxy infall) is a measure of the cluster potential well. However, this requires a very large number of galaxy velocities to be reliably measured [25] and still one will not be sure that the sample contains all clusters within a given volume and above a given mass . This simply because in the first place the cluster selection function was only loosely related to this fundamental parameter, which is what model predictions are based upon. This is a serious problem if one wants to do cosmology with clusters of galaxies, which means e.g. measuring their mean density or two–point statistics, because questions as simple as "What is the volume explored by my survey?" do not have an obvious answer when clusters are selected just as overdensities in the galaxy distribution.

4 X-ray Selected Clusters

X-ray selection represents currently the most physical way by which to identify and homogeneously select large numbers of clusters of galaxies[3]. Clusters shine in the X-ray sky thanks to the *bremsstrahlung* emission produced by the hot plasma ($kT \sim 1 - 10$ KeV) trapped within their potential wells. For this mechanism the bolometric emissivity (i.e., the energy released per unit time and volume) at temperature T scales as $\epsilon_T \propto n_e n_i T^{1/2}$, where n_e and n_i are the number densities of electrons and ions, respectively. The dependence on the density squared is one reason why the identification of clusters in the X-ray band is less affected by false projection effects. In fact, traditional optical selection based on galaxy overdensities depends only linearly on the density of galaxies. Fig.1 explicitly shows how in

[2]The 2dF [68] and SDSS [69] surveys represent the two largest efforts to date to reconstruct the galaxy distribution over a large portion of the local Universe ($z \lesssim 0.2$). The latter, in particular, is measuring redshifts for 1 million galaxies using a dedicated telescope, with additional photometric data in five bands for almost 10^8 galaxies.

[3]A notable powerful alternative is represented by radio surveys using the Sunyaev–Zel'dovic effect. This technique also probes directly the energy content of the cluster potential well: towards the cluster direction, the Cosmic Microwave Background photons are scattered through Inverse Compton by the energetic electrons of the intracluster plasma. An advantage of SZ is that the $(1+z)^4$ surface brightness dimming is compensated by a $(1+z)^4$ increase in the CMB energy density, which would make an SZ survey for clusters effectively flux–limited also at very large redshifts (see e.g. [4] for a review). Large-scale applications of this effect have been so far limited by technology issues, such that only about 20 clusters with observed effect are currently known, but one can foresee a rapid development in the coming years.

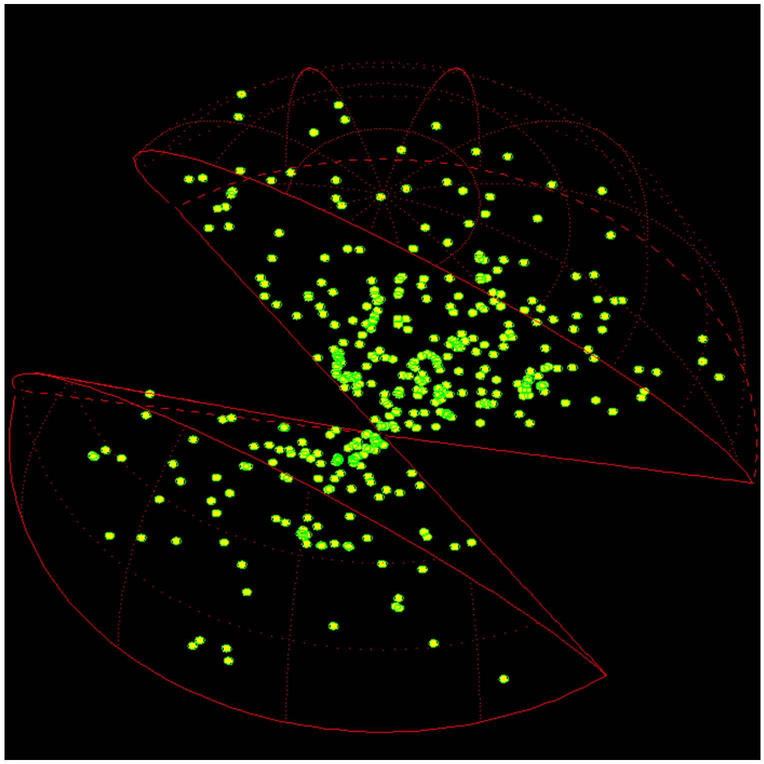

Figure 2: The spatial distribution of X-ray clusters in the REFLEX survey, out to 600 h^{-1} Mpc (from [7]). Despite the coarser mapping of structure, filamentary superclusters ("chains" of clusters) are clearly visible.

the X-ray band clusters emerge as single, mostly isolated, extended sources (virtually at any z), which can be unambiguously identified by an X-ray telescope with sufficient resolution and sensitivity. At the same time, the selection function of an X-ray cluster survey can be determined to high accuracy, knowing the properties of the X-ray telescope used, in a similar way to what is usually done with magnitude–limited samples of galaxies [57]. This is a crucial point if our cluster surveys are to be used as cosmological probes to address global properties and not only for studying single, yet interesting, objects.

The intracluster gas temperature, as measured through the observed X-ray spectrum, is the most direct probe of the potential well: $kT \propto \mu m_p \sigma_v^2 \sim G\mu m_p M_{vir}/(3r)$ (where m_p is the proton mass, $\mu \simeq 0.6$ the gas mean molecular weight, σ_v the galaxy 1D velocity dispersion and M_{vir} the cluster virial mass). Current large surveys of X-ray clusters are based on instruments with limited spectral resolution (essentially the ROSAT satellite) and this quantity is therefore not available in general. However, at least on a phenomenological basis, X-ray luminosity, a more directly observable quantity, shows a good correlation with temperature, $L_X \propto T^\alpha$ with $\alpha \simeq 3$ and a small scatter, $\lesssim 30\%$. Although one can debate at length about the physical processes that shape up such a relatively tight relationship (and there were a few discussions at the meeting on this subject, see e.g Moscardini and White contributions in this volume), this does not affect its practical usefulness: we can select clusters by X-ray luminosity and be sure we are selecting them by mass with an error estimated to be $\lesssim 35$ % when taking into account all uncertainties in the various steps [9]. Even if pre–heating processes as e.g. supernovae explosions are important in the overall cluster thermodynamics (and necessary, given the observed slope of the relation), it has been shown that these cannot perturb the temperature–mass relation at more than the 10–15% level [66]. Therefore, once we establish that the L–T relation is tight, the L–M will be as well and we can safely use L_X as possibly the cheapest reliable way to select clusters by mass. What is surprising is that this relation seems to hold rather well also at redshifts close to unity and above [15, 49, 16], which makes pre–heating even more necessary. Still, this means that we can safely make cosmological predictions for clusters of a given mass out to these redshifts and sensibly compare them with observed clusters of a given luminosity ([9, 48, 55, 65]). This is by far superior to any attempt to estimate the mass of clusters using an optical estimator, as e.g. richness [7] (although see [43] for a possible improvement).

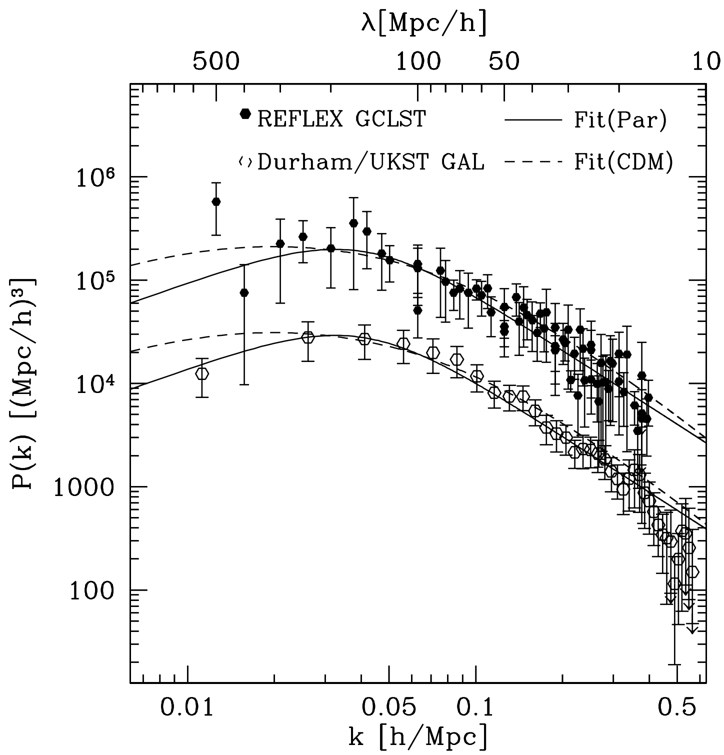

Figure 3: The power spectrum of REFLEX clusters (see [61] for details), compared to the galaxy power spectrum from the Durham-UKST survey [35]. The solid and dashed curves give the best fitting models using respectively a phenomenological shape and a CDM ($\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$) transfer function. Note how well the galaxy and cluster power spectra match each other's shape, implying a linear biasing independent of scale over this range.

5 Clustering of X-ray Clusters: Recent Progress

The study of clustering of optically–selected clusters has a long tradition, since the early pioneering work on the Abell catalogue [2, 38], and subsequent studies on automatic cluster catalogues as the EDCC [50] and APM [12]. Only in recent years similar clustering works have become possible on X-ray selected samples of clusters [39, 56, 51, 8, 47], mostly thanks to the completion of the ROSAT All–Sky Survey (RASS, see [72] for details).

The largest, statistically homogeneous sample of clusters with measured distances constructed so far from the RASS for clustering studies is the REFLEX (ROSAT-ESO Flux Limited X-ray) survey [5, 30]. The survey contains 452 clusters over the southern celestial hemisphere ($\delta < 2.5°$), at galactic latitudes $|b_{II}| > 20°$ and is more than 90% complete to a flux limit of 3×10^{-12} erg s^{-1} cm^{-2} (in the ROSAT band, 0.1–2.4 keV). Redshifts for all REFLEX clusters have been measured during a long observing campaign (1992-2000) using ESO telescopes. Fig. 2 plots the 3D distribution of REFLEX clusters within 600 h^{-1} Mpc, showing a number of superstructures with sizes ~ 100 h^{-1} Mpc. Despite the fading with distance due to the flux–limited selection function, it is visually evident how clusters are still strongly clustered among themselves. One of the main motivations for constructing this survey was to measure the power spectrum on scales approaching 1 h^{-1} Gpc. Fig. 3 shows an estimate of the power spectrum of REFLEX clusters (from [61]), compared to that of galaxies and to the best fitting CDM model (dashed line). This comparison is particularly significant because here, contrary to when comparing models to galaxy power spectra, the normalisation (i.e. the bias factor of the specific clusters used) is not a free parameter, but is computed given the well–understood mass selection function of REFLEX and the appropriate theory [45, 63]. In this way, it has been shown that an $\Omega_M \simeq 0.3$ model (open or Λ–dominated), best matches **both** the shape and amplitude of the observed REFLEX correlation function and power spectrum [11, 61]. The sensitivity of these quantities to variations in the value of Ω_M is shown by the plots in Fig. 4. From these plots, one can also appreciate the remarkable agreement in shape between galaxies and clusters on all scales, with the correlation function breaking down to zero around $60 - 70$ h^{-1} Mpc for both classes of objects. Such

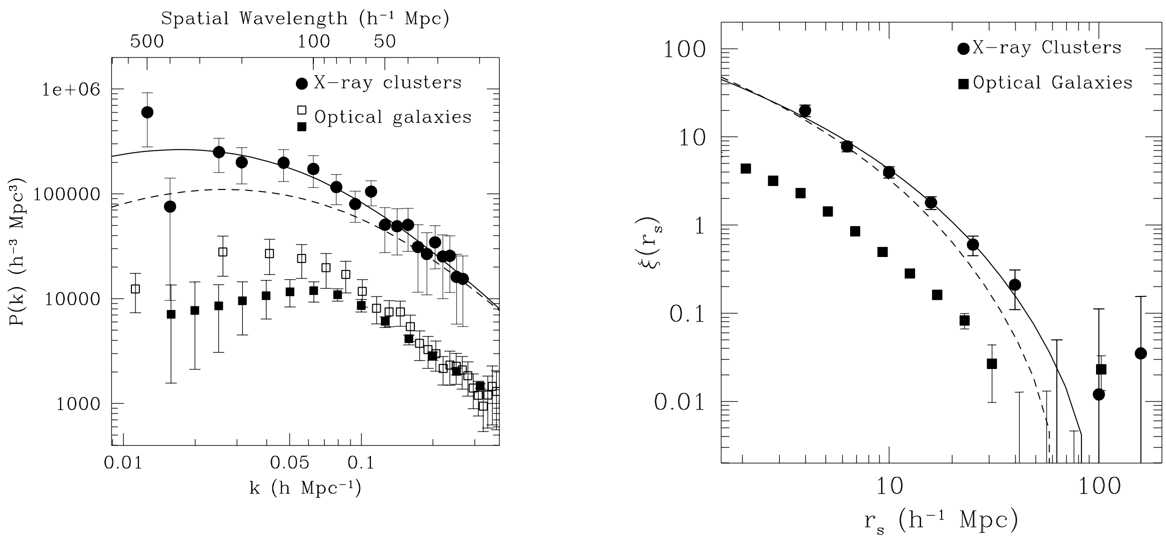

Figure 4: The sensitivity of model predictions for the REFLEX power spectrum and correlation function (filled circles) to even small variations in the value of the density parameter (solid line: $\Omega_M = 0.3$, as in fig.3 ; dashed line $\Omega_M = 0.5$, in both cases flatness is provided by $\Omega_\Lambda \neq 0$). (REFLEX estimates are from [61] and [11]; models and figures are from [7]). In addition to the Durham–UKST survey, here also the power spectrum of the Las Campanas Redshift Survey (LCRS [41], solid squares) is shown (note the lack of power in the latter power spectrum below $0.1\,\mathrm{h\,Mpc^{-1}}$, most probably due to an insufficient correction of the survey window function). In the right panel, the galaxy two–point correlation function is also from the LCRS [67].

simple proportionality was never seen so clearly with previous cluster samples and is a confirmation of the bias scenario where clusters form at the high, rare peaks of the mass density distribution [36]. It also confirms the reassuring view that at least above $\sim 5\ \mathrm{h^{-1}}$ Mpc the galaxy and *mass* distributions are as well linked by a simple constant bias.

One important point from Fig. 3 is how significant is the evidence for a turnover in the power spectrum at low k's. This issue has been addressed using the so–called Karhunen-Loeve transform to the REFLEX data, exploring volumes up to $1\ \mathrm{h^{-1}}$ Gpc size [62]. Such specific likelihood analysis which is based on finding the optimal basis of eigenvectors given the survey geometry [71], confirms the evidence for a turnover in the REFLEX $P(k)$ at $k = 0.023 \pm 0.006\,\mathrm{h\,Mpc^{-1}}$, providing a best fitting value for the CDM shape parameter $\Gamma = 0.14^{+0.13}_{-0.07}$. Similar power on these scales is seen in the 2dF galaxy redshift survey[4] [54].

Finally, Fig. 5 plots the two–point correlation map $\xi(r_p, \pi)$ for the REFLEX survey data. This function is used to evidence distortions produced by peculiar velocities on the observed galaxy and cluster 3D maps, which by definition are constructed in *redshift space*. In the REFLEX case, it shows for the first time a clear indication of infall of clusters towards superstructures [31, 11]. This result indicates that in most previous cluster samples this effect was masked by selection effects and redshift errors . Contrary to these, in this sample there is basically no elongation of the contours along the π direction (the line of sight component of the separation s between pairs, $s^2 = \pi^2 + r_p^3$), which tells us that both projection effects and redshift errors are negligible in this survey. On the other hand, the contours are significantly compressed at large r_p's: this is the fingerprint of streaming motions (see [53] for a discussion of these effects based on the Hubble Volume simulations), and is a function of the parameter $\beta = \Omega_M^{0.6}/b$ (see [29] for details and [68] for an application to the 2dF survey).

[4] Unfortunately, the 2dF $P(k)$ results (although published) could not be obtained in electronic form at the time of writing, and a direct comparison plot similar to Fig. 3 could not be done.

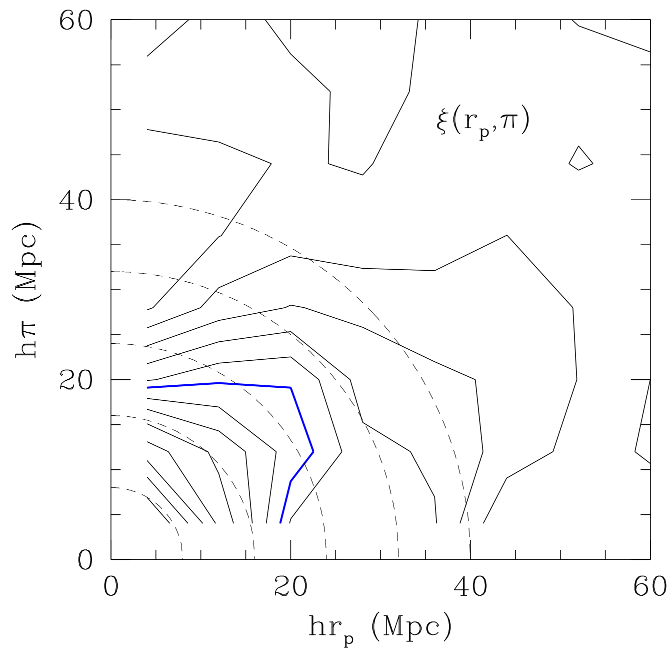

Figure 5: The bi-dimensional correlation function $\xi(r_p, \pi)$, used to evidence redshift–space anisotropies in the clustering of REFLEX clusters. This diagram shows how spurious anisotropies (as those expected from projection biases in the cluster catalogue construction) and redshift errors are negligible in the REFLEX survey (no stretching of the contours at small r_p's), while large-scale motions of clusters are detected (compression of the contours at large r_p's). The dashed circles show how a perfectly quiet cluster distribution would look like [11, 31].

6 Power on Gpc Scales and Features in the Power Spectrum

The REFLEX power spectra from the largest volumes available, tend to show significant power around $k \sim 0.02$, but still consistent with a CDM model with very low value of $\Gamma \simeq 0.14$, as stated above. Significant power in this range of scales is also expected if the baryonic contribution to the mean density is non–negligible with respect to the dark matter. In this regard, there has been significant interest in the last few years about the possibility of detecting other "baryon features", i.e. wiggles in the observed power spectrum amplitude produced by acoustic oscillations within the last scattering surface [18]. The observational results so far have been contradictory: Miller et al. [44] claim to detect oscillations through a joint statistical analysis of the power spectra from three different cluster+galaxy data sets. Interestingly, their finding is very consistent to what one would expect by just taking the best fitting set of cosmological parameters from the very last CMB observations [14] and computing the CDM+baryons transfer function. On the other hand, the wiggles visible in the latest 2dF power spectrum are currently not considered as particularly significant by the authors [54]. As an aside, it remains still a fascinating issue to understand whether one of these features, if confirmed, could be related to the "periodic" pattern detected more than 10 years ago by Broadhurst and collaborators [10] in their pencil beam surveys at the galactic poles (see [28] for more discussion of past results, and [60] for similar tentative indications from the 2dF QSO survey).

7 X-ray Clusters and the Evolution of Structure: Deep Surveys

Fig. 6 (from [7]) shows in a clear way how sensitive the evolution of structure is to the cosmological model, and in particular to the value of Ω_M. Clusters of galaxies basically describe the growth of structures within comoving volumes of $\sim 10\ \mathrm{h}^{-1}$ Mpc size, and one can notice how their abundance at even moderate redshifts is strikingly different in the two scenarios: massive systems are already quite rare at $z = 0.6$ and substantially absent at $z = 1.4$ in the Einstein–De Sitter model. This figure provides one of the main motivations for the deep surveys of clusters to $z \sim 1$ and beyond,

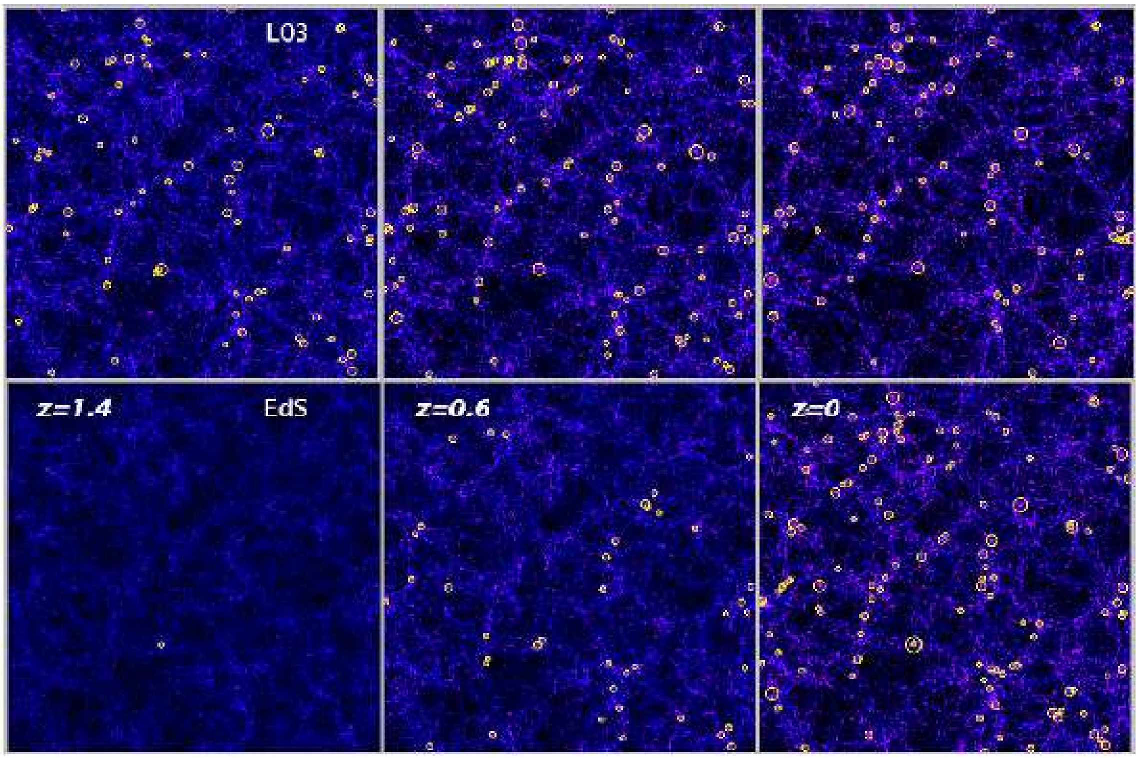

Figure 6: Redshift snapshots from two CDM n–body simulations with $\Omega_M = 1$ (bottom) and $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$ (top), showing how sensitive the evolution of the density of massive clusters (equivalent $T > 3$ keV, size of circles proportional to T) is to the value of the mean matter density Ω_M. Both simulations are normalised as to reproduce the correct abundance of clusters at $z = 0$ (from [7]).

that have been performed in recent years based mainly on the ROSAT PSPC archive. Such surveys constructed samples of serendipitously-observed clusters which have been used to measure directly the cosmic evolution of the mean density of X-ray luminous systems (see [34] and [59] for reviews). The lack of evolution in the X-ray luminosity function (XLF) for $L \lesssim L^* \simeq 4 \cdot 10^{44}$ erg s^{-1} out to $z \sim 0.8$ resembles the situation of the top panel of Fig. 6 (once we translate temperatures into luminosities), thus favouring low values for Ω_M (see [9] for details). At the same time, these results confirm the early findings from the EMSS [22, 33] of mild evolution at the bright end of the XLF [70, 52, 58, 23]. Fig. 7 plots a comparison of the latest XLF from the REFLEX survey, which represents the state of the art in the local ($z \lesssim 0.3$) Universe [6], to measurements at higher redshift [59]. Despite these strong observational efforts, however, the number of high–redshift X-ray selected clusters is still disappointingly small ($\sim$ 15 known above $z = 0.8$). Also, essentially all current large samples are based on the same ROSAT–PSPC instrument, including the most recent attempt to exploit the large area of the RASS to find massive clusters beyond the REFLEX limit (the MACS survey at $z \lesssim 0.6$ [17]). A different approach has been taken by a new survey, recently started after a thorough re–analysis of the higher–resolution ROSAT–HRI archive, a database so far neglected for cluster searches. This is the BMW (Brera Multiscale Wavelet) cluster survey [46]. Although still in the early phases of its optical follow–up, the BMW survey, which features a very interesting sky coverage to farly faint fluxes ($\sim$ 100 sq.deg around 10^{-13} erg cm^{-2} s^{-1}, 1 sq.deg at 2.5×10^{-14} erg cm^{-2} s^{-1}), is producing very promising first results (two clusters above $z = 0.8$ and a few $z \sim 1$ candidates, see also `http://www.merate.mi.astro.it/~guzzo/BMW/gallery.html`) and is expected to provide an important complementary "bridge" between the PSPC surveys and future (> 2003) surveys based on Chandra and XMM data (see e.g. Pierre, this volume).

Acknowledgements. I thank M. Treyer and L. Tresse for the wonderful organization of this meeting and for their patience with the proceedings. I am grateful to all my collaborators in the various projects discussed here and in particular to H. Böhringer, C. Collins and P. Schuecker. This paper draws freely from another review written together with S. Borgani, to whom I am deeply indebted. I also thank

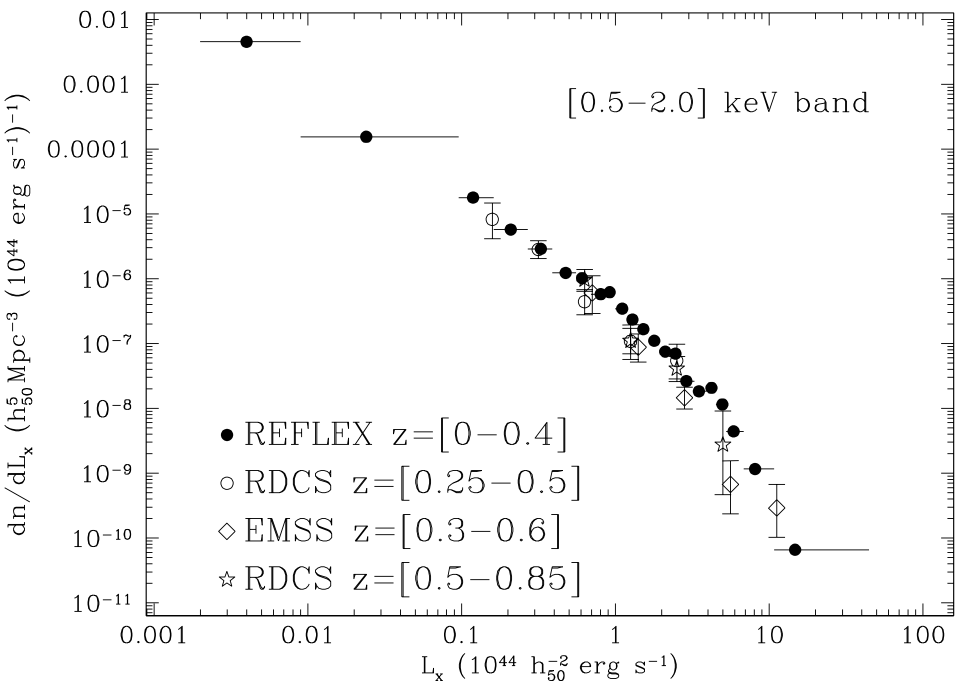

Figure 7: Comparison of the REFLEX X-ray cluster luminosity function at low z's [6], with that of two representative distant cluster samples, the RDCS [58] and EMSS [33], showing the moderate reduction in the number of very luminous clusters at high redshifts.

P. Rosati for very useful discussions on finding distant clusters and for access to his RDCS data, S. Borgani and A. Fernandez-Soto for critically reading the manuscript and A. Moretti for his help with figure 1.

References

[1] Abell, G.O., 1958, ApJS 3, 211

[2] Bahcall, N.A., Soneira, R.M., 1983, ApJ 270, 20

[3] Benoist, C., et al., 1999, ApJ 514, 563

[4] Birkinshaw, M., 1999, Phys. Rept. 310, 97

[5] Böhringer, H., et al. (the REFLEX Team), 2001, A&A 369, 826

[6] Böhringer, H., et al. (the REFLEX Team), 2001, ApJ, in press (astro-ph/0106243)

[7] Borgani S., Guzzo L., 2001, *Nature* 409, 39

[8] Borgani, S., Plionis, M., Kolokotronis, E., 1999, MNRAS 305, 866

[9] Borgani, S., et al., 2001, ApJ in press (Nov 2001 issue, also astro-ph/0106428)

[10] Broadhurst, T.J, et al., 1990, *Nature* 343, 726

[11] Collins, C.A., et al. (the REFLEX Team), 2000, MNRAS 319, 939

[12] Dalton, G.B., et al., 1994, MNRAS 271, 47

[13] Dalton, G.B., et al., 1997, MNRAS 289, 263

[14] De Bernardis, P., et al., 2000, *Nature* 404, 955

[15] Della Ceca, R., et al., 2000, A&A 353, 98

[16] Donohue, M., et al., 2001, ApJ 552, L93

[17] Ebeling, H., et al., 2001, ApJ 553, 668

[18] Eisenstein, D.J. , Hu, P., 1998, ApJ 496, 605

[19] Ellis, R., 2001, in "Lectures of the XIth Canary Island Winter School of Astrophysics", (astro-ph/0102056)

[20] Gal, R.R, 2001, PhD Thesis, California Inst. of Technology

[21] Giavalisco, M., et al., 1998, ApJ 503, 543

[22] Gioia, I., et al., 1990, ApJS 72, 567

[23] Gioia, I., et al., 2001, ApJ 553, L105

[24] Giovanelli, R. et al., 1986, ApJ 300, 77

[25] Girardi, M., et al., 1998, ApJ 505, 74

[26] Governato, F., et al., 1998, *Nature* 392, 359

[27] Guzzo, L., et al., 1997, ApJ 489, 37

[28] Guzzo, L., 2000, in *XIXth Texas Symposium on Relativistic Astrophysics & Cosmology*, Nucl. Phys. B (Proc. Suppl.) vol.80, p.233 (09/06), E. Aubourg et al. eds. (astro-ph/9911115)

[29] Guzzo, L., 2001, in "Clustering in the Universe: from Highly Nonlinear Structures to Homogeneity", *Graduate School in Contemporary Relativity and Gravitational Physics*, V. Gorini & U. Moschella eds., in press. (astro-ph/0102062)

[30] Guzzo, L. et al. (the REFLEX Team), 1999, *The Messenger* 95, 27

[31] Guzzo, L. et al. (the REFLEX Team), 2001, in preparation

[32] Hawkins, E., et al., 2001, MNRAS 325, 589

[33] Henry, J.P., et al., 1992, ApJ 386, 408

[34] Henry, J.P., 2001, in "AMiBA 2001: High-z Clusters, Missing Baryons, and CMB Polarization", in press (astro-ph/0109498)

[35] Hoyle, F., et al., 1999, MNRAS 309, 659

[36] Kaiser, N., 1984, ApJ 284, L9

[37] Kim, S.J., 2001, PhD Thesis, Princeton University

[38] Klypin, A.A., Kopylov, A.I., 1983, *Sov. Astron. Lett.* 9, 41

[39] Lahav, O., et al., 1989, MNRAS 238, 881

[40] Lazzati, D., et al., 1999, ApJ 386, 408

[41] Lin H., et al., 1996, ApJ 471, 617

[42] Lumsden, S.L., et al., 1992, MNRAS 258, 1

[43] Miller, C.J., Melott, A.L., Nichol, R.C., preprint (astro-ph/9912362)

[44] Miller, C.J., Nichol, R.C., Batuski, D.J., 2001, ApJ 555, 68

[45] Mo, H.J. & White S.D.M., 1996, MNRAS 282, 347

[46] Moretti, A., et al. (BMW Team), 2001, in "X-ray Astronomy 2000", R. Giacconi et al. eds., in press (astro-ph/0103348)

[47] Moscardini, L., et al., 2000, MNRAS, 314, 647

[48] Moscardini, L., et al., 2000, MNRAS 316, 283

[49] Mushotzky, R.F., Scharf, C.A., 1997, ApJ 482, L13

[50] Nichol, R.C., et al., 1992, MNRAS 255, P21

[51] Nichol, R.C., et al., 1994, MNRAS 267, 771

[52] Nichol, R.C. et al., 1999, ApJ 521, L21

[53] Padilla, N.D., Baugh, C.M., 2001, MNRAS submitted (astro-ph/0104313)

[54] Percival, W., et al. (the 2dF team), 2001, MNRAS 327, 1297

[55] Reiprich, T.H., Böhringer, H., 1999, *Astr. Nachr.* 320, 296

[56] Romer, et al., 1994, *Nature* 372, 75

[57] Rosati, P., et al., 1995, ApJ 445, L11

[58] Rosati, P., et al., 1998, ApJ 492, L21

[59] Rosati, P., et al., 2000, in "Large Scale Structure in the X-ray Universe", Plionis, M. & Georgantopulos, I. eds. (Paris: Atlantisciences), p. 13

[60] Roukema, B.F., et al., 2001, A&A submitted (astro-ph/0106135)

[61] Schuecker, P., et al. (the REFLEX Team), 2001, A&A 368, 86

[62] Schuecker, P., et al. (the REFLEX Team), 2001, in preparation

[63] Sheth, R.K., Mo, H.J., Tormen, G., 2001, MNRAS 323, 1

[64] Sutherland, W., 1988, MNRAS 234, 159

[65] Suto, Y., et al., 2000, ApJ 534, 551

[66] Tozzi, P., Norman, C., 2001, ApJ 546, 63

[67] Tucker, D.L. et al., 1997, MNRAS 285, L5

[68] Peacock, J.A., et al. (the 2dF Team), 2001, *Nature* 410, 169

[69] York, D.G., et al. (the SDSS Collaboration), 2000, AJ 120, 1579

[70] Vikhlinin, A., et al., 1998, ApJ 498, L21

[71] Vogeley, M.S., Szalay, A.S., 1996, ApJ 465, 34

[72] Voges, W., et al., 1996, in *Röntgenstrahlung from the Universe*, (H.U. Zimmermann et al.), MPE Report No. 263, p. 637

[73] Yair, S., Branchini, E., Dekel, A., 2000, ApJ 540, 62

[74] Zwicky, F., et al., 1961-68, *Catalogue of Galaxies and of Clusters of Galaxies* (Pasadena: California Institute of Technology)